ORKA: Precise Measurement of $K^+ \to \pi^+ \nu \bar{\nu}$ at Fermilab

David E. Jaffe

Outline

- Motivation
- E949 experimental method
- Improvements for ORKA
  - Detector acceptance
  - Kaon production and transport
- Sensitivity and backgrounds
- Cost and schedule
- Conclusions

Rare Decays in the LHC Era

Access to mass scales above 1 TeV

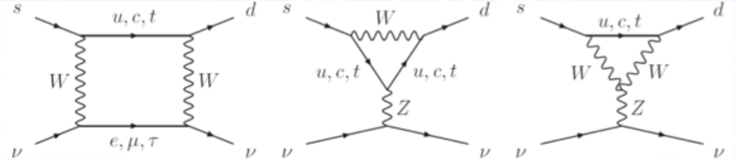
New Physics found at LHC	New Physics NOT found at LHC
New particles with unknown flavor- and CP-violating couplings	
$\Downarrow$	$\Downarrow$
Precision flavor-physics experiments needed to help sort out the flavor- and CPV-couplings of the NP.	**Precision flavor-physics experiments needed** to access mass scales beyond the LHC reach through virtual effects.
$\Downarrow$	$\Downarrow$

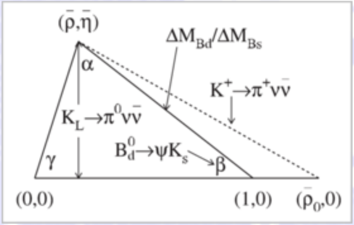
Q/L flavor	Special process to probe NP
1(2)	$\mu \to e\gamma$, $\mu \to e$ conversion, $\pi^+(K^+) \to e^+\nu$
2	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L^0 \to \pi^0\nu\bar{\nu}$
3(3)	$b \to s\gamma$, $B \to \mu\mu$, $(\tau \to \mu\gamma)$

Special status: small SM uncertainty and large NP reach

$K^+ \to \pi^+ \nu\bar{\nu}$ in the Standard Model

The $K^+ \to \pi^+ \nu\bar{\nu}$ decays are the most precisely predicted FCNC decays with quarks





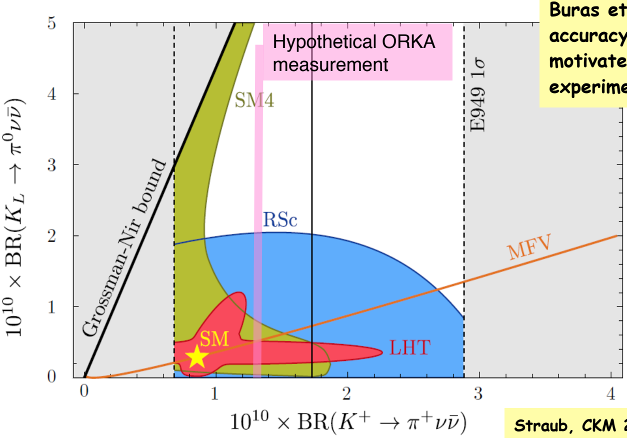
- A single effective operator $(\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)$
- Dominated by top quark (charm significant, but controlled)
- Hadronic matrix element shared with Ke3
- Uncertainty from CKM elements (*will improve*)
- **Remains clean in most New Physics models**

  (unlike many other observables)

Brod, Gorbahn, Stamou PR **D83**, 034030 (2011)

$$B_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (7.8 \pm 0.8) \text{ x } 10^{-11}$$

Sensitivity to New Physics



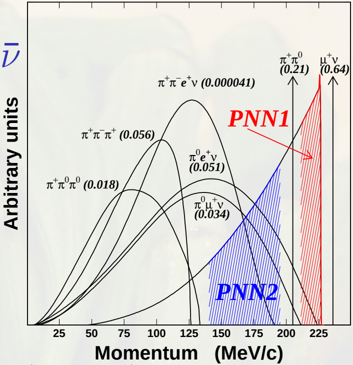
Buras et al. SM accuracy of <5%, motivates 1000-event experiments

Straub, CKM 2010 workshop (arXiv:1012.3893v2)

Figure 1: Correlation between the branching ratios of $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ in MFV and three concrete NP models. The gray area is ruled out experimentally or model-independently by the GN bound. The SM point is marked by a star.

Challenges of measuring $K^+ \to \pi^+\nu\bar{\nu}$

$\mathcal{B}_{\mathrm{SM}}(K^+ \to \pi^+\nu\bar{\nu}) = 0.000000000078$
$\mathcal{B}(K^+ \to \pi^+\pi^0) = 0.21$
$\mathcal{B}(K^+ \to \mu^+\nu) = 0.63$



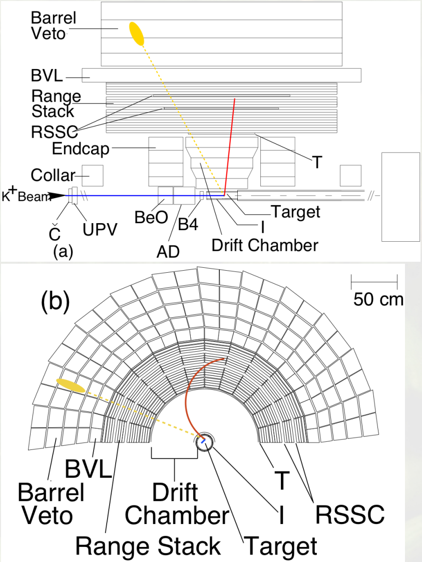
Experimentally weak signature with backgrounds exceeding signal by $> 10^{10}$

- Determine everything possible about the K^+ and π^+
  - π^+/μ^+ particle ID better than 10^6 ($\pi^+ \to \mu^+ \to e^+$)
  - Work in CM system (stopped K^+)
- Eliminate events with photons or extra charged particles
  - π^0 rejection $> 10^6$ (Every detector element is a veto)
- Suppress backgrounds well below expected signal (S/N$\sim$10)
  - Use "Blind analysis" techniques
  - Predict backgrounds *from data*: dual independent cuts
  - Test predictions with outside-the-signal-region measurements
- Evaluate candidate events with S/N function

E949 Experimental Method

In the standard model, 78 of 1,000,000,000,000 K^+ decays are to $\pi^+\nu\bar{\nu}$.

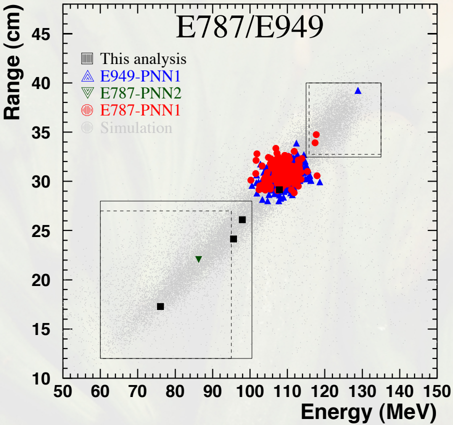
- **Measure everything possible**
- 710 MeV/c K^+ beam
- Stop K^+ in scintillating fiber target
- Wait at least 2 ns for K^+ decay (delayed coincidence)
- Measure π^+ momentum in drift chamber
- Measure π^+ range and energy in target and range stack (RS)
- Stop π^+ in range stack
- Observe $\pi^+ \to \mu^+ \to e^+$ in range stack
- Veto photons, charged tracks



E949/E787 Results

PNN1	E949	E787
Kaons	1.8×10^{12}	5.9×10^{12}
Bkgd evts	0.30 ± 0.03	0.14 ± 0.05
Acceptance	2.2×10^{-3}	2.0×10^{-3}
$N_{\rm obs}$	1	2
S/B	1.1	8, 59

PNN2	E949	E787
Kaons	1.7×10^{12}	1.7×10^{12}
Bkgd evts	$0.93 \pm ^{0.36}_{0.29}$	1.22 ± 0.24
Acceptance	1.37×10^{-3}	0.84×10^{-3}
$N_{\rm obs}$	3	1
S/B	0.20, 0.42, 0.47	0.20

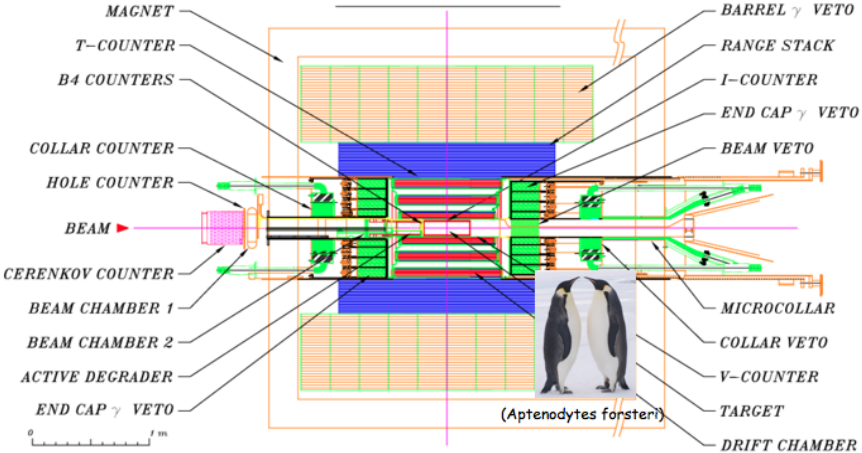


$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

$$\text{Standard model} \quad (0.78 \pm 0.07) \times 10^{-10}$$

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ was evaluated with a likelihood method that takes into account the signal-to-background ratio S/B of the individual candidates.

ORKA is a 4th Generation Detector
- x100 sensitivity -
x10 from kaon flux, x10 from detector



(Aptenodytes forsteri)

Detector Acceptance

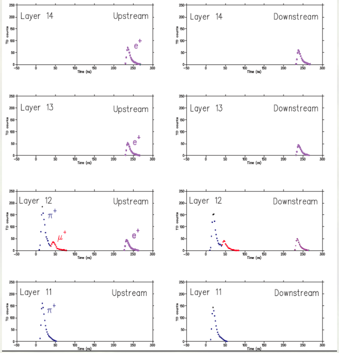
ORKA detector improvements will enable increases in signal acceptance.
Expected increases are based largely on E949/E787 data and measurements.

Component	Acceptance factor
$\pi \to \mu \to e$	2.24 ± 0.07
Deadtimeless DAQ	1.35
Larger solid angle	1.38
1.25-T B field	1.12 ± 0.05
Range stack segmentation	1.12 ± 0.06
Photon veto	$1.65^{+0.39}_{-0.18}$
Improved target	1.06 ± 0.06
Macro-efficiency	1.11 ± 0.07
Delayed coincidence	1.11 ± 0.05
Product (R_{acc})	$11.28^{+3.25}_{-2.22}$

Uncertainty estimates in acceptance factors based on E949/E787 data.

$\pi \to \mu \to e$ Acceptance Factors

1. Identify range stack counter where π^+ stops
2. Detect $\pi \to \mu$ decay in stopping counter
3. Detect $\mu \to e$ in stopping counter and neighboring counters



$\pi \to \mu \to e$ in E787/E949 range stack

Quantity	Acceptance	Range
π decay	0.8734	(3,105) ns
μ decay	0.9450	(0.1,10) μs
μ escape	0.98	
e^+ detection	0.97 ± 0.03	
Product	0.78 ± 0.02	
E949 acceptance	0.35	
Improvement factor	2.24 ± 0.07	

Detector Improvements and $\pi \to \mu \to e$ Acceptance

1. Eliminate 4x multiplexing of range stack (RS) waveform digitizers used in E949.
   - Reduced loss due to accidentals
2. E949 RS: 19 layers (1.9cm thick), 24 azimuthal sectors. ORKA RS: 30 layers (0.95cm thick), 48 sectors.
   - Reduced accidental veto loss (μ^+ and e^+)
   - Improved discrimination of π and μ
3. Increased RS scintillator light yield by higher QE photodetectors and/or better optical coupling.
   - Improved μ identification
4. Deadtime-less DAQ and trigger: $\pi \to \mu \to e$ acceptance improvements; rudimentary $\pi \to \mu$ identification was an essential component of the $K^+ \to \pi^+\nu\bar{\nu}$ trigger in E787/E949.

Livetime and Delayed-Coincidence Acceptance

Livetime	
E949 livetime	0.74
ORKA estimate	1.00
Acceptance increase	1.35

Macro-efficiency	
E949 average	0.76
E949 best week	0.84
MiniBooNE (FY08)	0.85
ORKA estimate	0.85 ± 0.05
Acceptance increase	1.11 ± 0.07

E949 required a delayed coincidence of 2 ns between the stopped kaon and the outgoing pion to suppress prompt backgrounds.

Delayed coincidence	
E949 acceptance	0.763
ORKA estimate	0.851 ± 0.035
Acceptance increase	1.11 ± 0.05

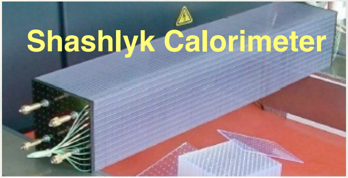
Improved Momentum and Range Resolution and Increased Solid Angle

ORKA/E949 momentum resolution	0.90	Increase B from 1 T
Acceptance increase	1.12 ± 0.05	to 1.25 T
ORKA/E949 range resolution	0.87 ± 0.05	More finely segmented
Acceptance increase	1.12 ± 0.06	range stack
E949/E787 energy resolution	0.93	Improved calibration
Acceptance increase	1.12	

Solid angle increase

	Drift chamber	Range Stack	Barrel veto	Lengths
E949	50.8	180	190	cm
ORKA	84.7	250	350	cm
Acceptance increase	1.38			

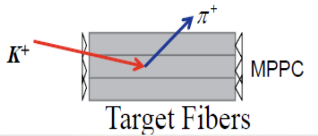
Photon Veto and Target Improvements



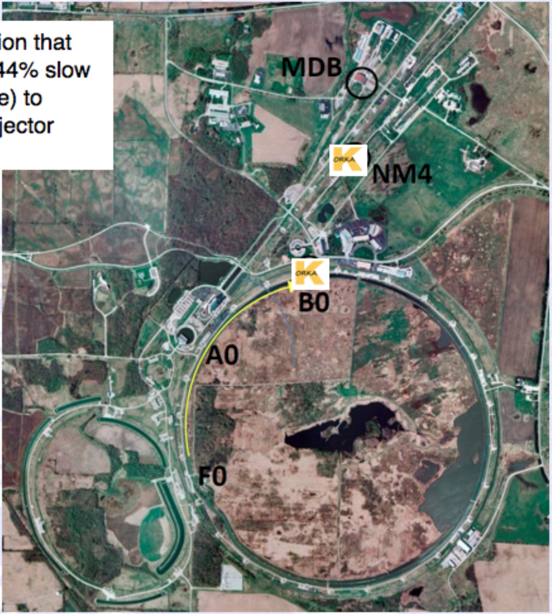
Photon veto	
E949	17.3 radiation lengths
ORKA	23.0 radiation lengths
Acceptance increase	$1.65^{+0.39}_{-0.18}$

Estimated increase taken from simulated KOPIO PV performance.
KOPIO simulation was adjusted to agree with E949 PV efficiency.

Target	
E949	3.1 m long, single-end
ORKA	1.0 m long, double-end
Acceptance increase	1.06 ± 0.06



ORKA is proposing a configuration that delivers 75kW (95 GeV) with a 44% slow spill fraction (4.4s spill, 10s cycle) to ORKA and a balance of Main Injector cycles to NOvA operations.



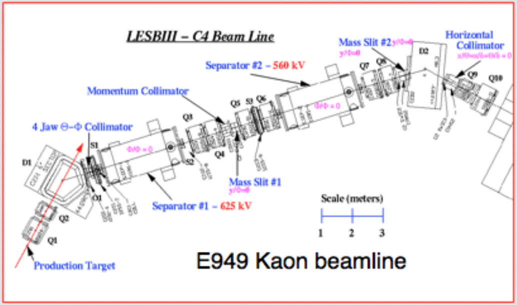
- **KTeV/Sea-Quest Hall:**

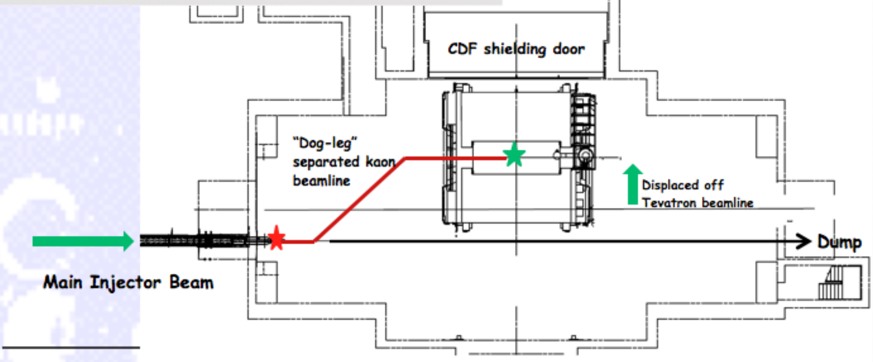
Existing beam transport, Rad firm, small hall, no magnet, existing and possible future Drell-Yan program.

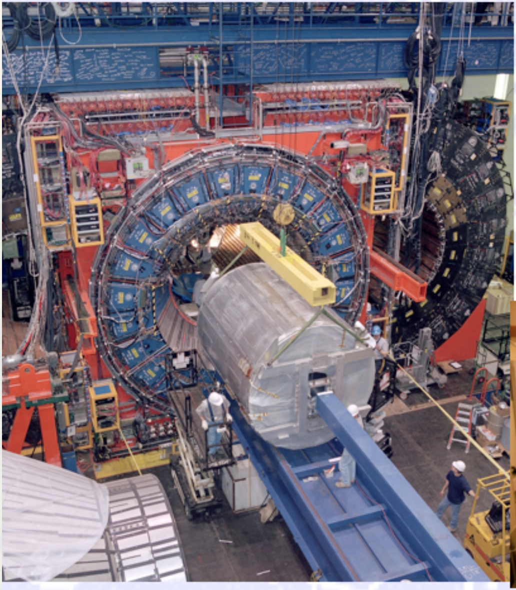
- **CDF(B0) collision hall:**

Existing tunnels and hall, Rad hard, adequate hall, magnet, A0->B0 beam-line required.

ORKA in the CDF Collision Hall







The ORKA new detector payload replaces the CDF tracker volume.

Steve Kettell with the BNL-E949 Central tracker (similar diameter to ORKA)

Rate of Incident Kaons

The expected rate of kaons incident on ORKA:

$$\begin{aligned} N_K(\text{ORKA})/\text{spill} &= N_K(\text{E949})/\text{spill} \times R_{\text{surv}} \times R_{\text{proton}} \times R_{K/p} \\ &= 12.8 \times 10^6 \times 1.4408 \times 0.7385 \times (6.5 \pm 0.8) \\ &= (88.5 \pm 10.9) \times 10^6 \quad . \end{aligned}$$

- $R_{\text{surv}} = 1.4408$, the relative rate of survival of 600 MeV/c kaons in the 13.74m ORKA K^+ beamline compared to 710 MeV/c K^+ in the 19.6m E949 beamline,
- $R_{\text{proton}} = (48 \times 10^{12})/(65 \times 10^{12})$ protons per spill,
- $R_{K/p} = 6.5 \pm 0.8$, the relative K^+ production rate into the ORKA and E949 kaon beamline acceptance as determined from MARS-LAQSGM simulation.

Instantaneous and stopped kaon rates

For a 4.4 s spill every 10 s, the kaon instantaneous rate is

$$N_K/\mathrm{s(inst.)} = (88.5 \pm 10.9) \times 10^6/4.4\mathrm{s} = (20.1 \pm 2.5) \times 10^6 \ K^+/\mathrm{s}$$

A K^+/π^+ ratio of 3.31 is expected, so the total instaneous rate would be 26.2 MHz compared to 8.4 MHz in E949.

For a kaon stopping fraction of 0.54 ± 0.12, in one year of running (5000 hours=18×10^6 s), the total number of stopped kaons in the experimental target is

$$\begin{aligned} N_{\mathrm{Kstop}}/\mathrm{year} &= (88.5 \pm 10.9) \times 10^6/10.0\mathrm{s} \times (18 \times 10^6 \ \mathrm{s}) \times (0.54 \pm 0.12) \\ &= (8.6 \pm 2.2) \times 10^{13} \,. \end{aligned}$$

$K^+ \to \pi^+ \nu\bar{\nu}$ Events per Year

The number of signal events per 5000-hour year is

$$
\begin{aligned}
N &= \mathcal{B}_{SM} \times N_{\mathrm{Kstop}} \times A_{\mathrm{E949}} \times R_{\mathrm{acc}} \times \mathcal{S}'_{\mathrm{loss}} \\
&= (0.781^{+0.084}_{-0.077}) \times 10^{-10} \times (8.6 \pm 2.2) \times 10^{13} \times (3.59 \pm 0.36) \times 10^{-3} \\
&\quad \times (11.3^{+3.3}_{-2.3}) \times (0.77 \pm 0.02) \\
&= 210 \text{ SM-level events per year}
\end{aligned}
$$

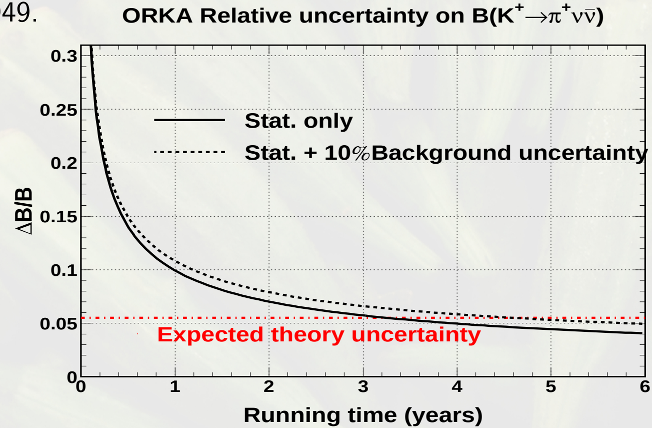
where

- A_{E949} is the E949 acceptance,
- R_{acc} is the product of acceptance factors gained over E949,
- $\mathcal{S}'_{\mathrm{loss}}$ is expected relative loss of acceptance due to the higher OKRA instantaneous rate

Due to the availability of considerable data from E949, we are able to provide a good estimate of the uncertainty in the SM-level signal yield for ORKA of approximately 40%. In contrast, many previous rare decay experiments encountered unexpected factors that led to large (even orders of magnitude) deviations from the initial sensitivity predictions.

Sensitivity and Backgrounds

- Kaon production at 95 GeV may introduce accidental hits in ORKA; no evidence in E787/E949 for background due to the primary beam. Assume same background sources in ORKA as E949.
- Assume the S/B ratio in the PNN1 & PNN2 subregions is the same as E949.



ORKA measurements & thesis topics

- $\mathbf{K^+ \to \pi^+\nu\bar{\nu}(1)}$ ^{T,P}
- $\mathbf{K^+ \to \pi^+\nu\bar{\nu}(2)}$ ^{T,P}
- $K^+ \to \pi^+\nu\bar{\nu}\gamma$
- $K^+ \to \pi^+ X$ ^{P}
- $K^+ \to \pi^+\tilde{\chi}_0\tilde{\chi}_0$(FF) ^{P}
- $K^+ \to \pi^+\pi^0\nu\bar{\nu}$ ^{T,P}
- $K^+ \to \pi^+\pi^0 X$
- $K^+ \to \mu^+\nu_h$ (heavy neutrino) ^{T}
- $K^+ \to \mu^+\nu M$ (M =majoran)
- $K^+ \to \mu^+\nu\bar{\nu}\nu$
- $K^+ \to \pi^+\gamma$ ^{TP}
- $K^+ \to \pi^+\gamma\gamma$ ^{P}
- $K^+ \to \pi^+\gamma\gamma\gamma$
- $K^+ \to \pi^+\mathrm{DP};\ \mathrm{DP} \to e^+e^-$
- $\Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$
- $\Gamma(K^+ \to \pi^+\pi^0)/\Gamma(K^+ \to \mu^+\nu)$
- K^+ lifetime
- $K^+ \to \pi^+\pi^0 e^+e^-$
- $K^+ \to \pi^-\mu^+\mu^+$ (LFV)
- $\pi^0 \to \mathrm{nothing}$ ^{T,P}
- $\pi^0 \to \gamma\mathrm{DP};\ \mathrm{DP} \to e^+e^-$
- $\pi^0 \to \gamma X$

^{T}E787/E949 Thesis ; ^{P}E787/E949 Publication; DP≡Dark Photon

The ORKA Collaboration

Ole Miss

UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ

- Sixteen institutes spanning six nations:
  Canada, China, Italy, Mexico, Russia, USA
- Five US universities now, in active discussion with several others
- Two US National Laboratories
- Leadership from US rare kaon decay experiments from the past 20+ years

New collaborators welcome!

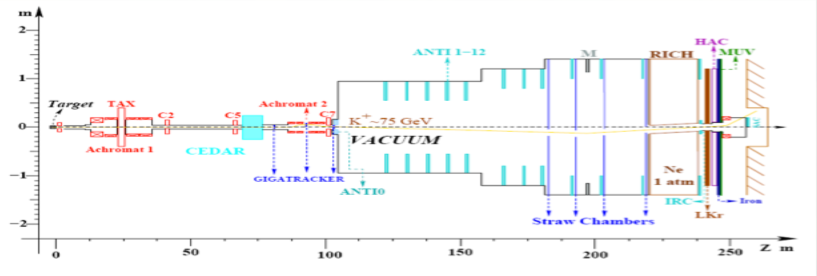
Cost and Schedule

Total project cost estimate of $53M (FY2010) based on E949 experience and FNAL FY99 fixed target operations. More work is needed after designs mature.

Milestone/Activity	**Time Period**
Stage One Approval	**Dec 2011**
DOE Approval of Mission Need (CD-0)	Fall 2012
Approve Alt. Selection/Cost Range (CD-1)	Spring 2013
Baseline Review (CD-2)	End of 2013
Start Construction (CD-3)	Spring 2014
Begin Installation	Mid-2015
First Beam/Beam Tests	End of 2015
Complete Installation	Mid-2016
First Data (CD-4)	End of 2016

$K^+ \to \pi^+ \nu \bar{\nu}$ Roadmap: ORKA and NA62

CERN NA62 decay-in-flight experiment. Builds on NA31/NA48 experience.



- Unseparated 75 GeV , GHz beam
- Aim: 40-50 SM events/year
- Majority of sensitivity in PNN2 region — complementary to ORKA
- Under construction; data-taking start > 2013
- **2017** NA62 results

NP? ORKA will provide a definitive measurement with a completely different method

No NP? ORKA will push the hunt for NP with much higher sensitivity

Conclusions

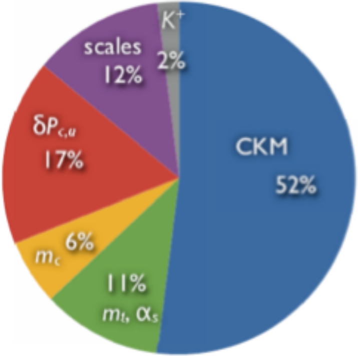
The Fermilab mission focus for the coming decades is accelerator-driven intensity frontier research. Precise measurement of $K^+ \to \pi^+\nu\bar{\nu}$ is broadly recognized to be one of the most compelling accelerator-driven intensity frontier experiments.

- ORKA proposal: 1000 event $K^+ \to \pi^+\nu\bar{\nu}$ measurement at FNAL MI
- Proven technique; experienced team; leveraged resources
- Guaranteed high-impact measurement
- Matches SM uncertainty; covers all accessible non-SM physics up to 1000 TeV mass scale
- Goal endorsed by HEPAP/P5 and Fermilab PAC
- Granted FNAL Stage One approval: Dec 2011
- Cost estimate \$53M (FY2010)
- Excels relative to competition at CERN

Extras

Summary of SM Theory Uncertainties

CKM parameter uncertainties
dominate the error budget today.



With foreseeable improvements, expect total SM theory error ≤6%.

A. Kronfeld

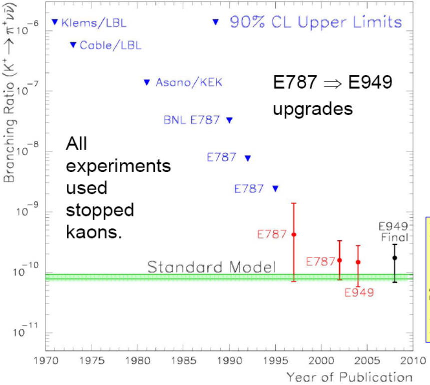
Unmatched by any other FCNC process (K or B).

30% deviation from the SM would be a 5σ signal of NP

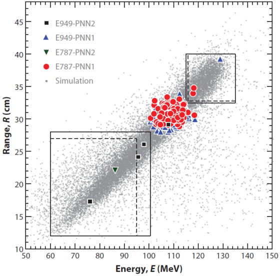
SM theory error for K_L^0 ® $\pi^0\nu\bar{\nu}$ mode exceeds that for K^+ ® $\pi^+\nu\bar{\nu}$.

U. Haisch, arXiv:0707.3098

$K^+ \to \pi^+ \nu \bar{\nu}$ History



Pion Range vs. Energy



E787/E949 Final: 7 events observed

$B(K^+ \to \pi^+ \nu \bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$

Standard Model:

$B(K^+ \to \pi^+ \nu \bar{\nu}) =$ (0.78+-0.08) $x10^{-10}$

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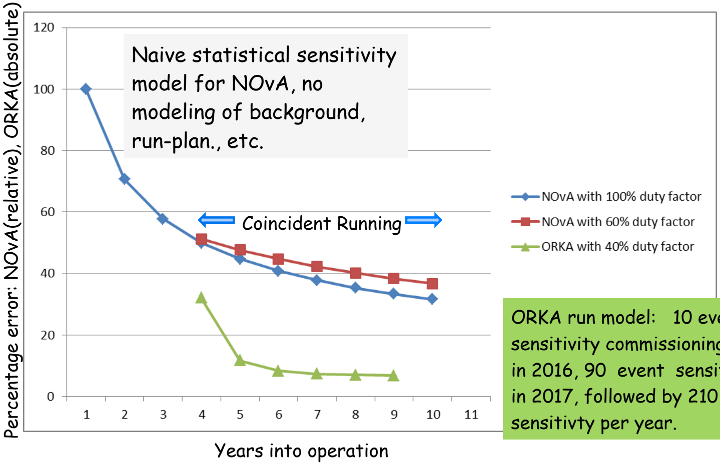
Consideration of NOvA and ORKA Joint Sensitivities



ORKA run model: 10 event sensitivity commissioning run in 2016, 90 event sensitivity in 2017, followed by 210 event sensitivty per year.

Sensitivity

- Under simple assumptions, the fractional precision of the measured $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ is comparable to the projected theoretical uncertainty of 6%.
- E949 has demonstrated that a likelihood-based technique can improve the sensitivity by taking into account the variation in S/B in the signal region.
- Extensive methodology to determine the background rates and signal acceptance from data was developed and refined by E949/E787. This methodology provides the basis for suppressing systematic uncertainties and enabling precise measurement of $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$.

E949/E787 Background, Acceptance and Results

PNN1	E949	E787
Kaons	1.8×10^{12}	5.9×10^{12}
Bkgd evts	0.30 ± 0.03	0.14 ± 0.05
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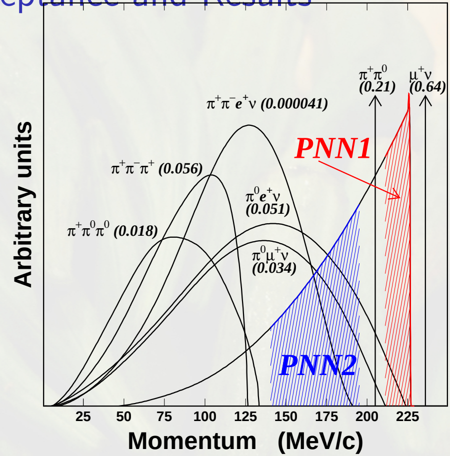
$N_{\rm obs}$	1	2
S/B	1.1	8, 59

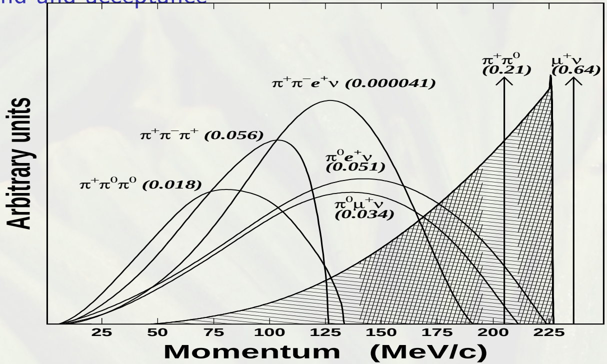
PNN2	E949	E787
Kaons	1.7×10^{12}	1.7×10^{12}
Bkgd evts	$0.93 \pm^{0.36}_{0.29}$	1.22 ± 0.24
Acceptance	1.37×10^{-3}	0.84×10^{-3}
$N_{\rm obs}$	3	1
S/B	0.20, 0.42, 0.47	0.20



The probability of all observed candidates to be due to background is 0.001.

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ was evaluated with a likelihood method that takes into account the signal-to-background ratio S/B of the individual candidates.

E949 background and acceptance



Background	PNN2	PNN1 Standard	PNN1 Extended
$K_{\pi2(\gamma)}$	$0.695\pm^{0.164}_{0.180}$	0.019 ± 0.004	0.216 ± 0.023
Muon	0.011 ± 0.011	0.015 ± 0.002	0.068 ± 0.011
K_{e4}	$0.176\pm^{0.244}_{0.143}$		
Beam	0.001 ± 0.001	0.007 ± 0.003	0.009 ± 0.003
CEX	$0.013\pm^{0.016}_{0.013}$	0.004 ± 0.001	0.005 ± 0.001
Total	$0.93\pm^{0.36}_{0.29}$	0.05 ± 0.01	0.30 ± 0.03
Acc.(10^{-3})	1.37 ± 0.14	1.69 ± 0.14	2.22 ± 0.17

Front-end electronics and redundancy

- Front-end electronics for each photodetector-based readout will consist of a base and signal splitter that feeds a waveform digitizer (WFD), an ADC and a multihit TDC.
  - The WFD would be a 500-MHz, 10-bit ADC.
  - The ADC would be a lower frequency WFD with more dynamic range.
- Experience with E949/E787 has shown that the redundancy provided by a TDC, ADC and WFD on each channel is important for high photon veto and signal detection efficiency.

$\pi \rightarrow \mu \rightarrow e$ acceptance factors

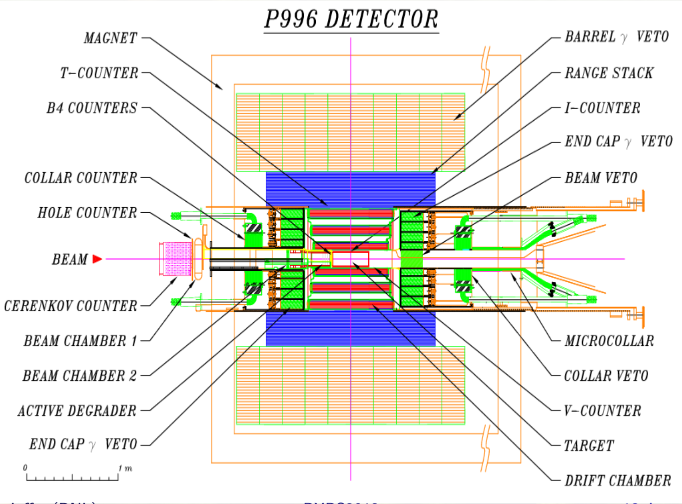
Positive identification of π^+ achieved by identification of $\pi \rightarrow \mu$ decay in range stack (RS) counter where π^+ stops and subsequent detection of $\mu \rightarrow e$ in stopping counter and neighboring counters.

Quantity	Acceptance	Range
π decay	0.8734	(3,105) ns
μ decay	0.9450	(0.1,10) μs
μ escape	0.98	
e^+ detection	0.97 ± 0.03	
Product	0.78 ± 0.02	
E949 acceptance	0.35	
Improvement factor	2.24 ± 0.07	

Lower time limit for pion decay driven by ability to resolve 3.0 MeV energy deposit of μ^+.
μ escape takes in account acceptance loss due to μ exitting stopping counter without depositing sufficient energy (1 MeV) for detection.

Solid Angle Increase

	Drift chamber	RS	Barrel veto	Lengths
E949	50.8	180	190	cm
ORKA	84.7	250	350	cm
Acceptance increase	1.38			



Livetime and delayed-coincidence acceptance

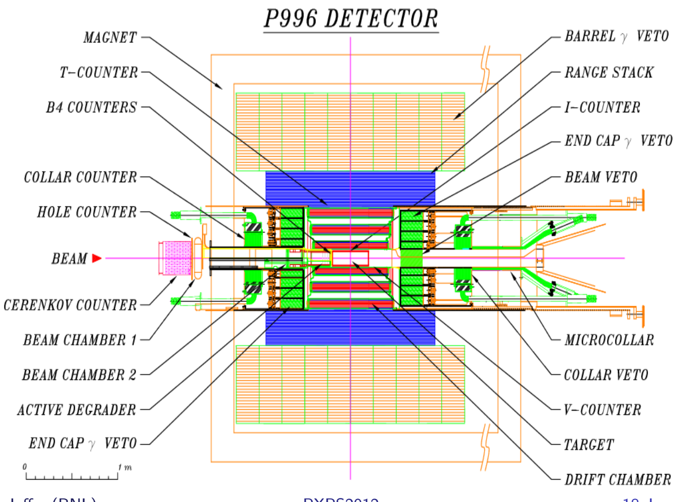
1. E949 had a typical deadtime of 26%. A deadtimeless DAQ and trigger would gain 1.35 in acceptance.
2. The "macro-efficiency" of the best week for E949 was 0.84 and is consistent with 2008 MiniBooNE and SciBooNE performance. An estimated ORKA macro-efficiency of 0.85 ± 0.05 represents a factor of 1.11 ± 0.07 improvement compared to the E949 average of 0.76.
3. E949 required a delayed coincidence of 2 ns between the stopped kaon and the outgoing pion to suppress prompt backgrounds. The overall online and offline acceptance of this requirement was 0.763 in E949. A deadtimeless DAQ and trigger are assumed to attain an acceptance of 0.851 ± 0.035 with a (2.0 ± 0.5) ns requirement for a gain of 1.11 ± 0.05.

Improved momentum and range resolution

1. Increasing the B-field from 1 T to 1.25 T improves the momentum resolution by 0.90. This improvement is estimated to increase the acceptance by 1.12 ± 0.05. (The energy resolution of E949 was improved by 0.93 compared to E787 and the acceptance increased by 1.12.)
2. A more finely segmented RS is estimated to improve the range resolution by 0.87 ± 0.05 which would give an acceptance increase of 1.12 ± 0.06.

Solid angle increase

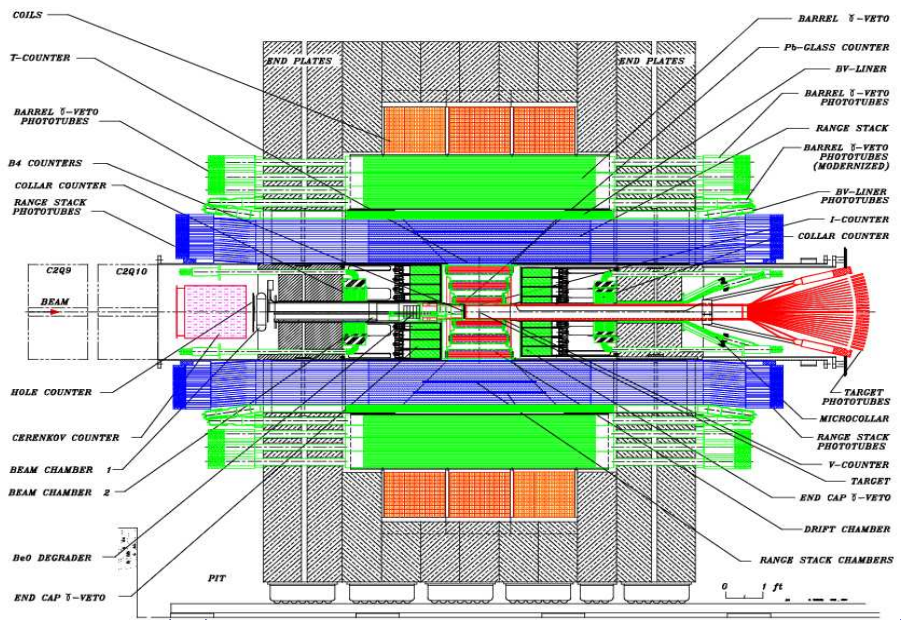
The E949 drift chamber was 50.8 cm long at the outer radius of 43.3 cm. A solid angle acceptance increase of 1.38 would be achieved by lengthening the drift chamber to 84.7 cm. This requires increasing the RS from 1.8m to $\sim$2.5 m and the barrel photon veto from 1.9m to $\sim$3.5 m.



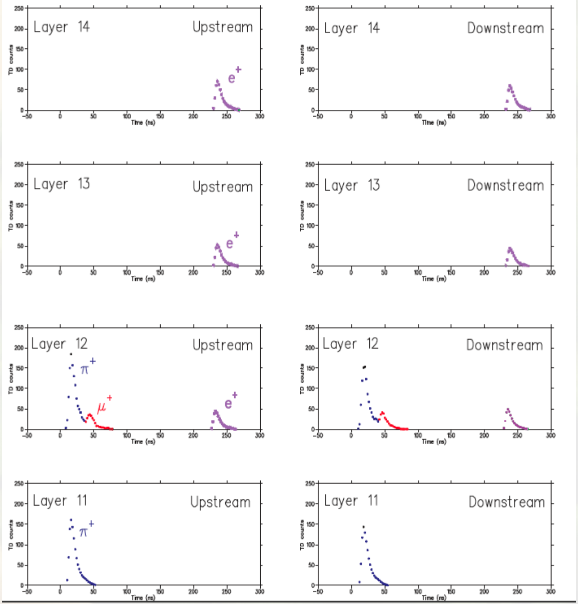
Photon veto and target improvements

1. The barrel region of ORKA would be 23 radiation lengths (rl) compared to 17.3 rl in E949 and is estimated to increase the acceptance by $1.65^{+0.39}_{-0.18}$.
   The estimate is based on simulation studies of the KOPIO ($K^0_L \to \pi^0 \nu \bar{\nu}$ experiment) photon veto of thicknesses of 16, 18, 21.6 and 26 rl. The KOPIO simulation was adjusted to agree with measured E949 photon veto performance.
2. The E949 scintillating target had 3.1m long, 5mm square fibers with single-ended readout. of each fiber. In ORKA, double-ended readout of a $\sim$1 m long target would increase the light yield and improve the measurement of the kaon decay point in the beam direction. The acceptance is estimated to increase by 1.06 ± 0.06.

E949 detector



$\pi \rightarrow \mu \rightarrow e$ detection in E949



Preliminary Total Project Cost Estimate (FY10 $M)

WBS element	Description	Total Cost	60% conting.	Total w/cont.
1.0	**Total Project Cost**	**33.3**	**20.0**	**53.3**
1.1	Accelerator and Beams	7.5	4.5	12.0
1.2	Detector	22.4	13.4	35.8
1.3	Project Management	2.7	1.6	4.4
1.4	Other Project Cost	0.7	0.4	1.1

- Based on E949 experience or Fermilab FY99 fixed target operations.
- Includes use of an existing solenoid.
- More work is needed after mature designs have been made.